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Logistic characteristics and requirements of Swedish wood biofuel heating plants

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ABSTRACT

The demand for wood biofuel for district heating plants and combined heat and power plants (CHPs) has increased, caused by an increase in both the number and size of CHPs. This places large demands on the logistics system supplying these plants with fuel, with a particular interest in the use of alternative modes of transport such as rail and sea. The aim of this paper is to identify the industry actors' requirements, constraints, and preferences regarding the wood-biofuel supply chain and to identify the logistical challenges this entails, as well as how this impacts the opportunity for an increased use of alternative transport solutions. A survey was sent to all Swedish CHPs, combined with six interviews with transport companies, terminal operators, and forest companies. The study shows that the industry has a local focus that limits potential logistics and sourcing solutions. It is also challenged by urban sprawl, with expanding residential areas close to the CHPs putting further constraints on the operations. Significant variations in fuel demand, depending on unpredictable outside temperature and seasonal variation, is a further challenge. The low density of the fuel has a negative impact on transport costs and introduces a trade-off between chipping close to the forest to increase density versus more efficient chipping at the CHP. Intermodal transport only used by large plants, driven by a shortage of local fuel.

1. Introduction

The negative effects of fossil-fuel usage are undisputed, and replacement with fuels such as biomass benefits the climate [1]. In the transition from fossil fuels to renewable fuels, the often higher cost of producing heat and electricity from biomass instead of fossil fuel is a major barrier [2]. In particular, the cost of procuring biomass is high, due to low bulk density [3], which makes efficient logistics crucial to the competitiveness of biomass [4]. In order to reduce costs, it is essential to have an efficiently and effectively designed supply chain. Traditionally, the fuel supply to biomass heating plants has mostly constituted road transport from local forests [5]. However, as both the size and number of the plants have significantly increased, this has created a demand for more advanced supply chains, including a need for long-haul transport [6]. This development has been particularly predominant in Sweden, where the use of biofuel for heating has increased by 109% between 2000 and 2018 [7], causing increased competition for fuel today [8] and even more in the future [9], increased prices [10] and occasional short term fuel shortages [11]. More large-scale plants are being constructed with, for example, the Igelsta combined heat and powerplant (CHP) outside Stockholm opening in 2009 and consuming about 100 tonnes of biofuel per hour [12]. The larger volumes and longer transport distances, combined with the environmentally friendly focus of biofuels, puts pressure on plants to look into alternative transport solutions and potentially reduce the use of road transport. New transport solutions are starting to emerge, with a focus on an increased use of intermodal transport. The Igelsta plant has, for example, invested €20 million in an eight-hectare rail terminal and is using both rail and ship to supply the plant [13]. These intermodal solutions have been successful and sparked much interest in the industry, with an increasing number of intermodal solutions being developed [6]. Smaller plants have also shown an interest in investigating in alternative transport solutions, supported by a strong political interest in reducing emissions. There is, therefore, a need for an increased understanding of the current supply chains and transport modes used, together with the perceptions and attitudes towards new transport solutions, in order to investigate the potential for alternative transport solutions and to ensure that biofuels remain a competitive energy alternative.

As well known in supply chain management, the design of any supply chain must meet the customer requirements (in this case the CHP) or it

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will certainly fail [14]. Given this background, the aim of this paper is, through a survey, to identify key characteristics, preferences, and logistical challenges of heating plants that set conditions for effective and efficient supply-chain design. As shown in the literature review in chapter 2, the study fills a literature gap by presenting the, to our knowledge, most extensive survey of preferences and requirements among CHPs. It provides empirical data on the situation in the industry and transport solutions used. Previous research lacks a comprehensive mapping of current supply chain practises among CHPs and in particular studies taking a wide supply chain perspective including both logistics setup and business operations. As the current study includes both the physical transport and business perspective in the same survey, this study contributes to a wider and more comprehensive understanding of the CHPs. The empirical data can further be used to validate previous research that has largely been based on modelling and in many studies on hypothetical cases [15].

The research question of the study is:

What are the key characteristics of the supply-chain solutions used by Swedish biofuel CHPs and how do the preferences and logistical challenges impact the opportunity for the increased use of alternative transport solutions?

The geographical scope of this research is energy producers in Sweden. As a country, Sweden was one of the pioneers in the usage of forest fuel for producing heat and electricity. In the 1970s, interest in biofuels as an alternative to fossil fuels emerged due to the oil crisis [16]. This development was particularly strong in Sweden due to environmental concerns [16] and strong policy support [17]. Sweden today has a large utilisation of forest fuels in district heating plants. District heating provides heating services to almost half the Swedish population, with wood fuels generating 21 TWh for district heating [18], corresponding to 17 million solid cubic meters of wood fuel [6]. Thus, Sweden has a long history of using forest fuel and constitutes a relevant case for understanding supply-chain design from the perspective of the energy producer. A comprehensive mapping of the Swedish biofuel CHPs is therefore of particular importance due to Sweden's position as an early adopter in the field [19].

The article is structured as follows. A literature review is presented in the next section, followed by a methods description and a presentation of the respondents' views of the current supply chain. This is then followed by analysis, discussion, and conclusions.

2. Literature review

The literature on biofuel transportation in a wide sense has increased since 2013 due to climate change and heightened environmental awareness. A review by Ref. [20] shows an increase from just 5 articles published between 2000 and 2006 to 181 articles between 2013 and 2018, although this refers to all types and aspects of biofuel supply chains with only a few articles focusing on CHPs and forest biofuel. A more narrow transport review by Ref. [5] identifies 117 papers since 1990 of which 44 focus on forest biofuel. It is clear from the reviews that the predominant methods of studying woodchip and CHP supply chains are quantitative modelling aiming at cost and/or emission calculations of the supply chain. For example, [4] makes an LP model on a national level of the Swedish transport system for heating plants identifying a savings potential of 22% from increased cooperation, [21] models supply chain costs to utilise more surplus forest biomass for heating plants in Sweden, [22] calculates the effects of introducing larger trucks for wood chips, concluding that this leads to lower transport costs. Extensive reviews of quantitative models have been provided, including one of 146 such models [23] and another of 124 [24], while [15] provides an overview of how biomass logistics operations are incorporated in mathematical models.

Intermodal transport has sparked particular interest [5] and has also largely been studied through quantitative methods. Examples of transport cost calculations include [25] who conducted a case study on a Swedish CHP and, as a result, revealed that large CHPs are needed to support intermodal transport. Eriksson [26] calculated the costs of several Swedish supply chain designs in order to compare the effects of chipping location, modes of transport and, transport distances etc. A similar comparative study, albeit based on a GIS model, was also performed in Finland [27]. In Canada [28], calculated that rail is more effective for long haul transport, while in Sweden [29] calculated the costs of an intermodal distribution system in a torrefaction supply chain. Optimisation and simulation have been applied by Ref. [30], for example, who used a simulation model to conclude that rail could efficiently increase the procurement area for a heating plant in Finland. Along similar lines [31], compared road and rail systems in California with a mixed integer model to find that rail is more effective for long-haul transport.

Although studies on intermodal transport have commonly included calculations of break-even points between road and rail, their results have varied widely: 386 km with densified biomass in a US case [32], 180–250 km with woodchips in a Swedish case [25], and 165 km and 145 km with woodchips in a Finnish setting [27] and a North American setting [28], respectively. Similar large cost differences can be found in the review by Ref. [5] on transportation costs, showing the high dependence on the case used in the modelling.

The studies show that there is potential in using intermodal transport, however, there is a lack of studies taking the perspective of the CHP and in particular trying to understand the demands and requirements of the CHPs and how these impact the transport system. Although an abundance of modelling studies have examined biofuel supply chains, few have investigated or mapped supply chain set-ups currently in use. In response to those gaps in the literature, a literature review was performed in Scopus using the words "heating plant" or "CHP" in combination with "supply chain", "transport", "intermodal", "rail", "sea", "road", "survey", "interview" or "actor" in the title, keywords or abstract. The search returned 187 potential articles for investigation, which once screened by title and abstract numbered only 20, all of which were studied in detail. After articles citing those articles and references in the articles themselves were studied as well, six relevant articles remained, as summarised in Table 1.

The review revealed a lack of literature with a broad perspective on CHPs or containing quantitative data describing the set-up of supply chains and their characteristics. As can be seen in Table 1, although some quantitative data are available in the papers by Ref. [34] and by Ref. [35] the data's scope is rather narrow, as this is not the main focus of the papers. Preferences are mapped in the papers by Refs. [33,36,38], although it is only the papers by Refs. [33,36] that links the preferences to the potential for intermodal transport. The intermodal papers do not publish any quantitative data, although their general findings are consistent with what can be expected in light of general research on the topic. The other two articles show somewhat different priorities in a quantitative ranking, most likely because [37] addresses the entire supply chain, whereas [38] focuses on HP/CHP but does not include transport preferences.

Altogether, few studies have followed wide, integrated approaches to presenting quantitative data covering all aspects of CHPs' supply chain designs and operations. In particular, no study has been found that attempts to link a detailed supply chain description with CHP preferences and their influence on the supply chain design.

To introduce the reader to the field, a general description of a typical supply chain is given in the following sections. A heating plant is typically located in, or very close to, an urban area, to which it is connected by the local district heating grid. Heat is generated by burning fuel at the plant, which is then distributed through underground pipes in the urban area for heating purposes. Large-scale heating plants are normally CHPs that also use heat to produce electricity, which provides more efficient utilisation than only generating heat or electricity.

A typical supply chain starts in the forest where the wood biofuels (trees, branches, stumps, etc.) are harvested. The biomass is then

Table 1
Summary of identified relevant articles.

Reference	Aim and method	Result(s)
Wolfsmayr and Rauch [33]	Interviewed Austrian CHPs and biofuel experts to map preferences and assess modal shift's barriers and drivers	Main barriers to modal shift and intermodal transport include negative experience with rail and a lack of infrastructure. Rail shows potential for transporting large volumes and transporting across long distances.
Karhunen et al. [34]	Questionnaire to Finnish CHPs to investigate domestic fuel security	Improving general operation conditions and the business environment can enhance fuel security. Quantitative data about fuel types and average storage capacity (0.3–70 days), number of suppliers (5–8) and sourcing distances (80 km).
Olsson et al. [35]	Interviewed 18 Swedish HPs and CHPs to investigate fuel security	Focus on supply risk management strategies. Divides in small, medium or large plants. Quantitative data on number of suppliers (1–25), number of daily deliveries (2–70), contract length (mostly annual) and fuel storage (i.e. 1–17 days). Transport dependent on road, particularly for small plants.
Flodén and Williamsson [36]	Conducted 13 interviews and eight site visits to study business models for intermodal biofuel transport	Four main business models are suggested. Discusses preferences, market structure, relationships and concludes that large volumes, long-term commitment, partnerships and a high level of competence in logistics are needed for intermodal transport.
Lloyd and Dey [37]	Questionnaire to 26 UK actors in the biofuel heating supply chain concerning the agreement with 39 statement in a wide range of aspects.	Respondents had little familiarity with supply chain terminology but nevertheless considered transport to be highly important. Important factors were direct transport, good supplier selection, storage and profitability.
Roos et al. [38]	Questionnaire to 68 Swedish heating plants on the agreement to 25 statements on fuel, suppliers and policies in order to map preferences.	Four generic types of HPs presented. Shows importance of environmental image, fuel quality, low cost, long-term contracts and policies.

normally transported by road, either directly to a power plant or to a terminal and/or storage area, where it is transhipped or stored [6]. The long-haul transport from a terminal to the plant/other terminal can also be performed by ship or rail; however, road transport is the most common option. Before being burned in the plant, the biomass needs to be reduced in size by chipping (or grinding) it into pieces of a few centimetres each. This is normally done roadside in the forest using mobile chipping equipment to increase the transport density of the often voluminous forest biomass, such as bulky branches, but chipping can also be performed at later stages of the transport chain using stationary equipment [6].

The wood biomass used is commonly logging residue (wood left in the forest after logging, such as the tree crowns and branches), but also is composed of lower grade tree stems, stumps, etc. Another origin point in the supply chain is the wood processing industry (e.g. sawmills) where by-products such as sawdust and wood shavings are collected.

A more detailed description of the supply chain can be found in the review by Ref. [39] or the description of Swedish state of the art [40].

3. Materials and methods

A web survey in Swedish was distributed via e-mail to a complete sample of managers at all 76 existing CHPs in Sweden that use biofuels. CHPs are located all over Sweden (see Fig. 1). Respondents not answering were phoned and urged to answer. The total response rate was 42% ($n = 32$). The survey was sent out during summer 2013; it contained 30–38 questions and was made adaptive to the answers given. For example, if the respondent did not use a certain type of fuel, the survey adapted and related questions were removed. An English translation of the survey is available in the Appendix.

The first part of the survey included questions about the current equipment and practices at the CHPs. These questions covered the general topics of storage, transportation, chipping, and overall supply-chain design. The second part investigated the perceptions of the CHPs towards current and desired practices regarding the transport of wood biomass, which involved ranking the different practices and issues on a scale.

The survey was supplemented by six telephone interviews and one e-mail interview to road (1), rail (1), and sea (e-mail) biofuel transport companies, a terminal company (1), a forest company (1), and energy companies (2). The interviews lasted about 60 min each and were recorded.

The combination of a survey and interviews provides the benefits of both methods. The survey gives a broad quantitative overview of the situation in the market, while the qualitative interviews provide an in-depth understating of individual actors in all parts of the supply chain. The understanding of the full supply chain gained by the interviews further helps us in interpreting the survey results. Fig. 2 provides an

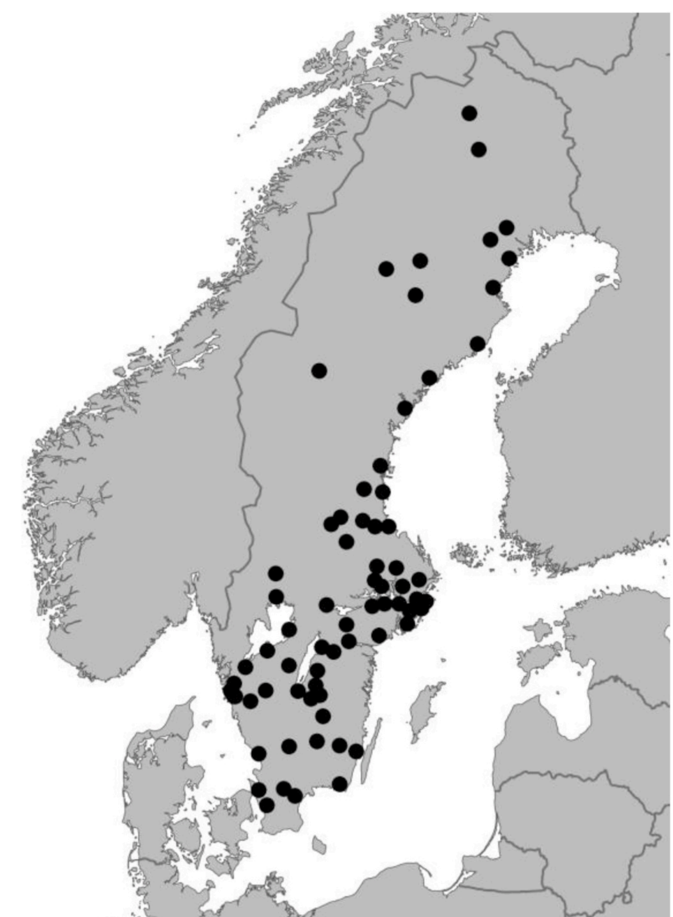

Fig. 1. Map of CHPs in Sweden.

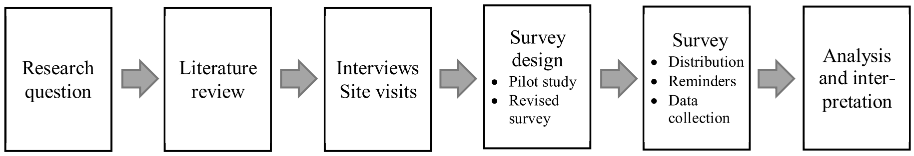

Fig. 2. The research process.

overview of the research process. Since the survey was conducted, there has been no significant changes to the industry. Approximately 20 new CHPs have been built in Sweden with a further 5–10 CHPs being planned [41]. The trend with increasing fuel demand and longer transport distances has continued. Transport of woodchips in general in Sweden by road has increased by 26% (tonne-km) [42] and rail transport have increased by 46% (tonne-km) [43,44]. Competition has increased in the electricity market with reduced prices causing CHPs to focus more on heat production [45].

4. Results

This section shows the results from the survey and the interviews, starting with fuel used, followed by chipping, transport, delivery, and supply-chain aspects.

4.1. Energy and fuels

Respondents are classified into three sizes: small (<250 GWh annual energy generated), constituting 41% of respondents and 11% of energy; medium (250–750 GWh), 34% of respondents and 31% of energy; and large (>750 GWh), 25% of respondents and 58% of energy. Total energy produced by surveyed CHPs was 16.3 TWh (12.2 TWh, winter, October–March; 4.0 TWh, summer, April–September), or 51% of the energy production (31.7 TWh) by CHPs in Sweden [18]. The share of electricity produced is 18% (winter) and 16% (summer). Large seasonal variations in fuel demand exist, as heating demand is dependent on outside temperature: 75% of energy is generated during winter, which is similar for all CHP sizes [large (L): 76%, medium (M): 75%, small (S): 71%].

The CHPs use a mix of different fuel types, with larger CHPs possibly having several boilers using different types. Boilers are adjusted to specific fuel mixes for maximum efficiency, and interviews showed that two seemingly similar plants might have different fuel requirements, and that specific details of a fuel (e.g. requested moisture content) might differ. On average, the CHPs use 3.5 types of the eight listed fuels (Table 2) (L:3.8, M:3.8, S:3.2). Wood chips are the most used fuel (64% of energy and used to some extent by 94% of CHPs). Chips are mostly made of logging residue, followed by chips made of other wood and of unknown wood. Based on respondents' comments in the survey and interviews, other wood is to a large extent recycled wood (waste from construction, etc.), but also includes bark and sawdust. Other fuels are reported as consisting of household waste, oil, paper, and similar items. Essentially, the same fuel mix is used all year.

Unless otherwise stated, the results presented in this paper are based on the share of energy for the full year. "Biofuels" refer to all fuels apart from "other fuels" in Table 2.

Table 2
Fuel used and share of energy.

Fuel	Winter (%)	Summer (%)	Total (%)
Logging residue chips	24	22	23
Chips of other wood	22	26	23
Chips of unknown wood	9	9	9
Stem chips	9	6	8
Pellets	6	6	7
Peat	7	3	6
Stump chips	1	1	1
Other fuels	22	27	23
Total	100	100	100

A total of 50% of the biofuel is sourced directly from the forest (S:58, M:43, L:53), while 27% (S:35, M:29, L:25) is sourced as by-products from the forest industry. In 17% of cases (S:7, M:27, L:12), the CHP does not know the origin of the fuel. Import is used to a limited extent (6%) by larger CHPs (S:0, M:1, L:10). In general, fuel prices are lower outside Sweden, which makes import economically possible, but the challenge is to keep transport costs down. Respondents attribute the lower prices to the fact that the district heating grid is less developed outside Sweden and thus carries a lesser demand for fuel. Also, as many of the international plants only produce electricity, instead of both electricity and heat as is common in Sweden, their purchasing power is lower. See also [46] for an overview of district heating in Europe and [36] for a description of the business relationships and business models in the industry.

The average number of biofuel suppliers is 14. Smaller CHPs have fewer suppliers compared to larger ones (S:6, M:14, L:30). Most have one major supplier, which represents on average 44% of supply (S:61, M:37, L:25), with second and third suppliers accounting for 21% (S:25, M:22, L:17) and 15% (S:19, M:11, L:13), respectively.

4.2. Chipping and storage

Chipping of wood biofuels is mostly performed roadside in the forest, where the harvested biofuel is chipped by smaller mobile chipping equipment (40% of chipped fuel, S:43, M:50, L:3), followed by an equal share of chipping at terminals (20%, S:33, M:30, L:10), at the CHP (20%, S:6, M:10, L:29), and at an unknown location (20%, S:18, M:10, L:27). Smaller CHPs prefer to receive the fuel already chipped, while chipping at the CHP is preferred by the large CHPs due to perceived better control over the fuels, lower chipping costs, better quality, and higher efficiency brought about by using larger stationary chipping equipment. Environmental aspects are also mentioned as equipment at terminals and CHPs can be powered by electricity. Obstacles stated for chipping at CHPs are local laws prohibiting chipping at CHPs in urban areas due to noise and dust, as well as the high volume needed to be economically feasible. It can be noted that the preferences are in line with what is actually used, indicating that the preferences are met (see Table 3).

As the need for fuel is dependent on the volatile demand for heat brought about by unpredictable outside temperatures, there is a need for storage. Interviews show that many CHPs consider this to be their supplier's problem. Contracts commonly stipulate an annual volume to be delivered, with a request made the week before (normally on Thursday) of what is needed the following week. Contracts are commonly signed on a yearly basis for each winter season; often, the same supplier as the previous year is used. Contracts for several years also exist. Volumes are expected to be flexible and often defined within ranges (+/− X%) in the contract. When adjusting the planned deliveries of fuel, changes normally have to be made between three days (22%) and one week (41%) in

Table 3
Preference of chipping location (1 = not at all preferred, 6 = very much preferred).

Chipping location	Total	Small	Medium	Large
Chipped at the forest	4.6	4.0	5.2	4.4
Chipped at the terminal	4.1	4.7	4.1	3.1
Chipped at the CHP	3.4	2.7	3.2	4.9

advance. Changes seldom cause any conflicts, although respondents do not think the system works well and called it a "guessing game", underlining the importance of planning ahead to secure a good supply of fuel. The vast majority (94%) of CHPs have storage options: 88% have storage at the CHP for biofuel; 6% store only at an external site close to the plant; and 29% have storage at both locations. Only two respondents (two of the smallest plants in the survey) claim to have no storage at any location. Storage facilities at the CHP are often smaller than the close-by storage, as CHPs commonly are located in city areas with limited available space because they must be connected to the local district heating grid. Therefore, the size of storage can vary significantly between CHPs of similar size.

Storage is considered not to cause any major problems for the CHPs, which is also supported by the interviews. More storage possibilities at the CHPs would be preferred, but the current situation is accepted as extended storage are often physically impossible (see Table 4).

4.3. Transport

Biofuel is normally transported directly from the source without intermediate storage or terminals (53%). The use of terminals and storage is more predominant in transport chains originating in the forest than in the forest industry. There are greater possibilities of arranging direct transport of by-products from the forest industry, as these flows are already consolidated in larger volumes at the sender and are more predictable as they depend on the production rate in the industry.

Terminals are more common among larger CHPs with larger and more complex flows, although the smaller CHPs use more intermedia storage (see Table 5). Respondents stated a desire to avoid terminals due to costs, although the use of terminals is perceived to be increasing.

Distances are short, with almost half the energy (48%) transported less than 100 km (see Table 6). A further 21% is from unknown distances; disregarding this, a total of 61% of the energy is from known distances less than 100 km. Long transports are unusual as 91% of the known distances are less than 500 km. Due to the low value and density of the biomass, the actors try to keep the transport distances as short as possible.

Road is the most common mode of transport in the CHP supply chain (see Table 6). All CHPs get some deliveries by road, and as many as 78% (S:85, M:82, L:63) have their entire fuel demand transported by all-road only. In particular, road is almost the only mode used with distances <250 km. In total, 83% of the energy is transported by all-road. An important factor is access to infrastructure at the sites. Rail access is only present in 19% of the CHPs and used by one large CHP. Ship access is present at 13% of CHPs and is used by 9% (S:0, M:9, L:25). It can be noted that, although the respondents claim that some fuel is transported by sea or rail only, it is likely that these chains also contain some elements of road transport that is perceived to be outside the supply chain, such as road haulage from the harvest sites in the forest to the port/rail terminal.

For deliveries performed by road, the most common load units/vehicles are fixed or tilting superstructure trucks, which are used to some extent by 90% of the CHPs (for 67% of the road-delivered energy), followed by hooklift container trucks by 77% of the CHPs (25% of the energy). Hooklift container trucks use detachable open-top biofuel containers adapted for low-density biofuel. Conventional 20-foot ISO containers are not used by any respondent. Tilting trucks are equipped to tilt the superstructure sideways to unload the biofuel. For trains, the special biofuel container Innofreight WoodTainer is the only load unit used.

A total of 78% (energy) of transport is arranged by the biofuel suppliers. Larger CHPs are more active in organising transport, while the smaller ones, to a greater extent, have their transport arranged by their suppliers (S:94, M:73, L:76). More than half [58% (S:92, M:100, L:0)] have their transport completely arranged by suppliers. Interviews showed that the CHPs mostly arrange transport from their own close-by storage and from the forest industry to their plant. External transport providers are contracted on a yearly basis, although the larger CHPs might have up to five-year contracts. Similarly, the supplier also pays the transport costs for 73% of the energy, and 45% (S:54, M:50, L:25) of the CHPs have all their transport costs paid by the supplier.

The mode of transport is decided by the CHP for 47% of the CHPs, by the supplier for 42%, and by the transport company for 11%. This is supported by the interviews, which showed that the CHPs retain influence over transport and would not allow any transport system to be used against their will. It is notable that the transport company is only a decision maker among the small CHPs and not in any of the other categories. Using rail and sea transport has been considered by 37% and 41%, respectively, of CHPs not currently using the modes. Several respondents commented on a lack of infrastructure for these modes.

Most CHPs are unaware of the transport costs for rail (82%) and sea (76%). Apart from the CHPs already using the modes, only one CHP in each category claims to understand the cost level. Also, for road, 29% claim to be unaware of the costs, all of which are small CHPs. It is noteworthy that several of the respondents claiming to be unaware of the costs still state that they pay the transport costs, probably indicating that transport is included in the price of the biofuel. On a scale of 1–6, where 1 is low cost, the average cost level was stated as 4.3 for road, 5.3 for rail, and 2.8 for sea, with no difference between summer and winter.

Respondents preferences when selecting mode of transport show a high focus on reliability, although most factors receive a rather high rating (see Table 7). Reliability is commonly ranked very highly in logistics (see, e.g. Ref. [47], for a review). It is noteworthy that environmental sustainability was ranked fifth of the seven options, since biofuel is often marketed as an environmentally friendly alternative. Interviews showed that respondents consider sustainability important, but focus is on delivering heat at low cost. Many CHPs are municipally owned and are further constrained by local political directives on purchasing, which often do not allow them to pay extra for sustainable transport.

Rating the services received, transport operators under-performed compared to service desired on several of the most highly ranked services (reliability, contamination, and cost level), while they over-performed on the lowest ranked services (frequency and transport time), indicating a possibility for improvement.

Road is very clearly the most preferred transport mode (see Table 8). Looking at positive properties associated with the transport modes, road is also rated most favourably as four of the seven properties received above 50% agreement among respondents (see Table 9). A comparison can be made with Table 7 showing that road matches two of the top three criteria. It is noteworthy that environmental sustainability, for which the road category had no agreeing respondents, contrasted with rail and sea, which had their highest scores here. For combinations of transport modes, a majority of the respondents did not agree to any of the properties. The interviews identified the large volumes needed for viability and inflexible system design as the main challenges to the use of rail and sea. Rail transport, in particular, has to be planned and scheduled months before the winter season, with limited possibilities for deviations.

The respondents did not identify any major problems related to transport, indicating a relatively well-functioning transport system (see Table 10). The low density of biofuel was considered the largest challenge, which also relates to the ranking of transport problems with

Table 4
Mean ranking of storage problems (1 = not at all problematic, 6 = very much problematic).

Storage issues	Total	Small	Medium	Large
Size of storage facilities	3.8	4.0	3.3	4.3
Location of storage facilities	3.7	3.8	3.4	3.9
Handling of biofuel at storage facilities	3.4	3.5	3.1	3.6
Availability of equipment at storage facilities	3.1	3.2	3.1	3.1

Table 5
Transport chains used.

Transport chain	Share of biofuel energy per year				Share of respondents using the option per year			
	Total	Large	Medium	Small	Total	Large	Medium	Small
Forest								
direct	29%	30%	27%	40%	69%	50%	80%	73%
via storage	9%	6%	10%	18%	34%	38%	30%	36%
via terminal	8%	10%	6%	0%	21%	25%	40%	0%
via both storage and terminal	4%	7%	0%	0%	7%	25%	0%	0%
Forest industry								
direct	24%	20%	27%	33%	59%	63%	60%	55%
via storage	0%	0%	0%	2%	7%	0%	10%	9%
via terminal	0%	0%	1%	0%	3%	0%	10%	0%
via both storage and terminal	3%	5%	0%	0%	3%	13%	0%	0%
From abroad	6%	10%	1%	0%	14%	25%	20%	0%
Unknown	17%	12%	27%	7%	24%	38%	30%	9%
Total	100%	100%	100%	100%	–	–	–	–

Table 6
Transport chains and distances (percentage share of energy).

Mode	Distance (km)	Total	Small	Medium	Large
Road only	<100	48	5	18	25
	100–250	13	1	6	6
	250–500	2	–	1	1
	>500	3	–	<1	3
	Unknown	17	4	4	9
Rail only	500–750	1	–	–	1
Sea only	250–500	4	–	–	4
	>750	1	–	–	1
Rail, then delivery by road	250–500	2	–	–	2
	500–750	2	–	–	2
Road, then delivery by rail	Unknown	4	–	–	4
Road, then sea, delivered by road	<250	2	–	2	–
	500–750	<1	–	<1	–
	<750	<1	–	<1	–
	Unknown	<1	<1	–	–
Delivery by road, previous steps unknown	<250	1	1	–	–
Conveyor belt	–	<1	<1	–	–
Total all modes		100	11	31	58

different fuels, where the ranking largely follows the density of the fuels [48].

4.4. Delivery

On average, the CHPs receive deliveries from 21 trucks per day (L:45, M:21, S:6) during winter and four during summer (L:8, M:4, S:1). The largest CHPs can receive as many as 70 trucks per day, or one truck on average every 13 min, during their opening hours, sometimes causing queues. In addition to this, several of the large CHPs receive deliveries by rail and sea. Opening hours to receive fuels are flexible, with most CHPs open weekdays, 06.00–22.00, with most fuel received during daytime. Some CHPs are open 24 h per day, 7 days per week, although most report that local regulations prohibit deliveries during night and weekends to avoid disturbing the neighbours.

Trucks have the shortest unloading time, with an average of 27 min at the plants, including all activities from when the vehicle arrives at the gates (administration, unloading, waiting time, etc.). However, estimates range from 5 to 60 min. Rail is unloaded at 4 h, or 3.6 min per load unit (66 per train), at both plants and terminals. Unloading of ships shows a greater variety, with 15–48 h and ship sizes ranging from 2000 to 4000 tonnes. The unloading time does not seem to correspond to the ship size.

The most common handling equipment available at the plants and storage facilities are wheel loaders [CHP (C): 91%, Storage (S): 100%] where only the smallest plants lack a wheel loader. Other common handling possibilities include the possibility to manage hooklift containers (C:59, S:45), an open handling area for arranging load units, etc. (C:34, S:64), fixed cranes (C:22, S:9), and forklift trucks to handle detachable load units (C:13, S:18). Larger CHPs have more handling possibilities than the smaller ones.

4.5. Supply-chain and industry perspective

From an overall supply-chain perspective, the most important factors in the biofuel supply chain are no contamination in the fuel, fuel quality, on time deliveries, and fuel price (see Table 11). As when selecting

Table 8
Preferences (1 = least preferred, 6 = most preferred) of different transport modes.

Preference	Total	Small	Medium	Large
Road	5.5	5.5	5.6	5.3
Rail	2.5	2.3	2.5	2.9
Road and sea combined	2.5	1.8	3.1	2.8
Sea	2.3	1.5	2.6	3.1
Road and rail combined	2.3	2.3	2.3	2.5
Road, rail, and sea combined	2.2	1.6	2.7	2.4

Table 7
Importance of service properties when selecting transport setup and satisfaction with received services (1 = not at all fulfilled/important, 6 = very much fulfilled/important).

Service	Importance				Satisfaction			
	Total	Small	Medium	Large	Total	Small	Medium	Large
High reliability	5.1	5.0	5.6	4.5	4.8	4.9	4.8	4.4
Few contaminations in the fuel, e.g. stones	4.9	4.8	5.2	4.6	4.2	4.6	4.1	3.7
Good access to the transport system, e.g. infrastructure	4.7	4.2	5.4	4.8	4.8	4.8	4.9	4.6
Low cost	4.7	4.3	5.2	4.6	3.9	4.1	3.9	3.7
Environmental sustainability	4.5	3.8	4.9	5.0	4.0	4.4	3.6	4.0
High frequency	4.2	3.9	4.9	3.5	4.7	4.8	4.9	4.3
Short transport time	3.8	4.0	3.9	3.4	4.6	4.5	4.8	4.6

Table 9
Qualities of transport modes (share of respondents agreeing).

	Low cost (%)	Short transport time (%)	High reliability (%)	Have high frequency (%)	No contamination in the delivered fuel, e.g. no stones (%)	Environmental sustainability (%)	Have good access to the transport system, e.g. infrastructure (%)	None of the above characteristics (%)
Road	17	55	69	59	3	0	72	3
Rail	7	0	14	0	0	54	0	39
Road and sea combined	11	4	11	4	0	30	19	52
Sea	21	0	7	0	4	43	7	46
Road and rail combined	7	4	7	4	0	22	15	59
Road, rail, and sea combined	7	0	7	0	0	22	7	63

Table 10
How problematic fuel types are to transport (1 = not at all problematic, 6 = very much problematic).

	Total	Small	Medium	Large
Transport of logging residues	3.0	3.0	3.0	3.2
Transport of tree parts	3.1	3.1	3.1	3.2
Transport of wood chips	2.5	2.5	2.6	2.5
Transport of pellets	2.3	2.1	2.3	2.8
The availability of suitable transport	3.0	2.8	3.4	2.7
The low density of biofuel	3.6	3.6	3.6	3.5
Risk of contamination of the biofuel during transport, e.g. stones	3.5	3.3	3.4	3.9

transport mode (see Table 7), the overall priorities are similar, with a focus on reliability and cost issues. Comparing the preferences and services received reveals that the CHPs are in general satisfied with their supply chain, although suppliers only meet their full expectations on the flexible delivery option. With all other factors, the service received is less than its importance. The low scores given to the low cost of transport and biofuel, in comparison to their high importance, is particularly noteworthy.

Respondents were also asked about their perceptions of the Swedish biofuel industry. The respondents perceive a good balance between supply and demand currently in Sweden, where the increasing demand for biofuel is expected to level off as most major CHP/HPs in Sweden soon will be converted to biofuel plants (see also [9]). However, they see a risk of other industries influencing fuel demand, e.g. potential increases in bioethanol production or economic fluctuations in the paper mill industry, which uses high-quality wood chips for pulp. Export of biofuel is not considered feasible due to comparably high biofuel prices in Sweden as well as transport costs. A main obstacle is the limited development of district heating in Europe, which keeps down the demand for biofuel and the fuel price.

On a more general level, the largest problem perceived was seasonal variation in demand for heating. Also, the dependency on Swedish political decisions ranked high (see Table 12). In the interviews, a clear distinction could be made between CHPs and other actors, where the other actors were not perceived to be dependent on politics. CHPs are often municipally owned and more subject to direct political influence, while the biofuel industry in general is also subject to a higher degree of political interest. At the same time, the interviewees perceived Sweden to be a world leader in biofuels for CHP due to the early political decision to build extensive district heating, which created a market (see for example [19]). In general, the market appears well functioning with no major cooperation problems or lack of fuel.

5. Analysis

The study shows a fairly well-functioning system for biofuel transport, although it also indicates a number of logistical challenges and areas for potential improvement that will be elaborated below. Respondents show a trust in the system and have not experienced any incidents in which the CHP could not be supplied. At the same time,

Table 12
Issues in the Swedish biofuel industry (1 = not at all problematic, 6 = very much problematic).

Issue	Total	Small	Medium	Large
Seasonal variations in the demand for heating	4.3	4.2	4.1	4.8
Dependence on Swedish political decisions on biofuels	4.1	4.3	3.8	4.4
Dependence on foreign political decisions on biofuels	4.0	4.3	3.4	4.3
Biodegradation of the biofuel	3.9	3.6	3.5	4.8
Contamination of the biofuel at delivery, e.g. stones	3.5	3.3	3.4	3.9
Drying of biofuel	3.3	3.0	3.4	3.8
Impact on the Swedish biofuel market from increased global demand for biofuels	3.1	3.4	2.9	2.8
Cooperation between actors in the industry	3.0	2.9	2.9	3.3
Standardized terms and definitions for biofuels and raw materials	2.7	2.5	2.7	3.1
The availability of biofuel	2.6	2.8	2.5	2.3

Table 11
Importance of service properties for the supply chain and satisfaction with current supply chain (1 = not at all fulfilled/important, 6 = very much fulfilled/important).

Properties	Importance				Satisfaction			
	Total	Small	Medium	Large	Total	Small	Medium	Large
No contamination in the delivered fuel, e.g. no stones	5.6	5.6	5.7	5.4	4.1	4.4	4.1	3.5
Good quality biofuel	5.5	5.5	5.5	5.4	4.5	4.5	4.6	4.3
Low biofuel price	5.4	5.5	5.5	5.1	3.5	3.8	3.6	2.8
On-time deliveries	5.4	5.5	5.3	5.4	4.4	4.8	4.4	4.0
Small environmental impact	5.0	4.8	5.0	5.3	4.2	4.1	4.3	4.1
Flexibility concerning ordered volumes	5.0	5.2	5.0	4.6	4.4	4.8	4.4	4.0
Deliveries evenly distributed in time	4.8	4.6	4.7	5.1	3.9	4.3	3.8	3.3
Low-cost transport	4.8	4.7	5.0	4.5	3.6	4.0	3.4	3.4
Flexibility concerning delivery options	4.3	4.0	4.5	4.6	4.3	4.2	4.4	4.1

respondents point to the fact that demand is uncertain, which makes planning difficult; transport costs are perceived as high, and the system is subject to a high degree of influence from political decisions. They further describe a transport system with a local focus, high dependence on road transport, and many local actors. The system largely operates on a short-term basis, with orders for fuel only placed a few days before delivery, due to uncertain future heating demand and a lack of large-scale storage sites. Intermodal transport is present only among the larger CHPs, constrained by the need for large volumes to make it profitable and a lack of access to suitable infrastructure.

5.1. Energy and fuels

There is a local focus in the supply chain. Road transport is only economically viable for shorter distances, and other transport modes require large transport volumes. In this way, the market is limited for smaller CHPs, which are essentially restricted to sources within 100 km of the plant by road. Larger plants have more sourcing options but also prefer local sourcing if possible. Many plants, in particular medium-sized CHPs, are unaware of the origins of their biofuel, indicating that they buy it as a commodity from their supplier. Smaller plants source very locally and thus have better knowledge of the biofuel origins, while the very large plants put great effort into their sourcing and logistics strategies to secure the large amount of fuel needed.

Lack of local fuel is the main driver for long-distance sourcing, as transport costs seldom make it possible for long-distance fuel to match local prices. In Sweden, the competition for biofuel is most intense in the densely populated central-eastern regions [8] while there is a potential surplus in other regions [21]. In contrast to many other industries, a CHP does not have the option of moving to a more favourable sourcing location as it must be connected to the local district heating grid. This local focus is further fuelled by a dispersed geographical structure with few CHPs in a region, which prevents cooperation on sourcing [36], although studies have shown that a co-operative strategy could reduce transport costs [49]. The local focus poses a logistical challenge as it limits the potential logistics solutions and is an obstacle to more advanced logistical and supply-chain setups, such as intermodal transport.

A clear difference can be seen in procurement between products obtained directly from the forest and forest-industry residues such as sawdust from sawmills. The forest chain is a pull-chain, where the CHPs order the amounts they need. The industry residues are a push-chain, where industry production sets the pace by which the by-products are produced. Contracts often state that the CHP agrees to accept all by-products produced, as the industry sees it as a waste product that it needs to be rid of. Power in the chains varies: the CHP is the channel leader in the forest chain, and the supply chain is set according to the CHP's needs, while the forest industry is the leader in the industry chain, and the chain is set according to the industry needs. However, consolidated and predictable fuel supply from the forest industry allows for better planning in the supply chain and enables the use of more direct transport.

5.2. Chipping and storage

Short-term storage is a vital part of the wood-biofuel supply chains, as unpredictable and fluctuating outside temperatures create a varying demand for heat. This poses a logistical challenge. Most industries are faced with an unknown future demand, but CHPs are extreme in being dependent on climate, which is impossible to predict accurately for more than a few days. Further, long-term storage is needed to balance the large demand differences between winter and summer. In a wider perspective, storage is also needed for at least a few months to dry the fresh biomass and reduce the moisture content [50]. However, this drying normally takes place in the forest directly after harvesting and is considered part of the harvesting process by the actors and not part of their supply chain.

From a logistical point of view, storage provides greater flexibility in designing the supply chain, enables more efficient transport flows, and is a requirement in high volume flows (e.g. ships and trains) supplying more than the immediate fuel need. Low-cost storage can help reduce overall costs [51]. A challenge is the limited storage space at CHPs that has forced them to utilise external storage at added cost. Urban sprawl, combined with very high investment costs (€100–200 million for a medium-sized CHP) make CHPs almost impossible to move, further placing pressure on potential storage areas and activities at the plant, as old CHPs increasingly find themselves located inside new residential and commercial areas. This leads to restrictions on noisy and dusty chipping and limits late-night deliveries. Urban sprawl poses a logistical challenge and refers to the sometimes unplanned way in which urban areas expand into surrounding areas and change the use and characteristics of the area (see, for example [52], for a definition and [53] for an overview of urban sprawl in Europe). The impact on CHPs can, for example, be seen in Copenhagen, where the newly built waste-to-energy plant "Amager Bakke" was designed with an artificial ski slope for the public on top of the plant [54], or in the process of establishing the Basel CHP [55].

The location of the chipping process has a large impact as it increases the density of the fuel and thereby influences the possible transport options and number of vehicles needed. The low density of the fuel poses a logistical challenge. The closer to the forest the chipping takes place, the more efficient the transport utilisation becomes as wood chips can be packed more densely than voluminous branches [4]. However, this has to be balanced against the more cost-effective chipping with higher quality that can be achieved at terminals and CHPs. The concentrated higher volumes make it possible to invest in expensive but more efficient equipment that also can be powered in a more environmentally friendly way by electricity. Large CHPs with higher volumes also express a greater preference for CHP chipping, although this reduces transport utilisation. However, most chipping currently takes place in the forest, which suggests that the current balance of efficiency lies there. Attempts to overcome this challenge, including, for example, compacting the unchipped fuel by bundling [56], have so far not achieved widespread use [57]. The opposite is true for the already compact round wood that has reduced density after chipping and therefore is better chipped close to the CHP.

5.3. Transport

The preference for road transport is very clear, as CHPs' preferences for high reliability, good access, and high frequency are well met by road transport. This, in combination with short transport distances, often makes road the only realistic transport option. These requirements pose a logistical challenge as they limit the use of potentially more sustainable and cost-efficient transport modes or combinations of modes. Other transport modes have problems matching the requirements, with the exception of environmental sustainability, where sea and rail are rated high and road is rated low. A major challenge for sea and rail is the lack of infrastructure access to the CHPs. This can be overcome by intermodal transport, where several transport modes are combined [58]. Transportation of wood biofuels consumes the most fossil fuels in the wood-biofuel supply chains [59], and previous studies indicate that the use of intermodal transport with road and rail have lower energy requirements and could also bring lower costs. Trains and ships carry large volumes and have low running costs per unit km, but have less frequency and require long transport distances for the high start-up and terminal costs to be outweighed by the lower running costs [25]. The cost difference between road and intermodal road-rail solution gives a break-even point at about 180–250 km haulage distance, depending on transport set-up and train utilisation. Break-even point can be further reduced to 120–190 km if the need for pre-haulage is reduced (see Ref. [25] for a more extensive cost comparison). The biofuel supply chain has potential for intermodal transport due to the wide use of storage and transhipment terminals that can serve as intermediate points in the chain. This also reduces added intermodal transhipment costs as the fuel is already transhipped at terminals. Intermodal transport is slower than road transport, although fast transport was ranked as having low importance.

5.4. Delivery

The delivery process is similar at all CHPs and appears well functioning. Larger plants supplied by road can experience queues due to the large number of trucks delivering. Urban sprawl constrains delivery options as an increasing number of residential areas close to the CHPs pressure them to reduce the amount of disturbing late-night traffic and unloading.

5.5. Supply-chain and industry perspective

The supply chains are characterised by fluctuating demand and are dependent on buffer stocks. The supply chain must be flexible to adapt to these changes, but at the same time, the low value and density of the fuel puts pressure on keeping the costs down. Although the supply chain does not completely meet the CHPs' expectations, it is still performing well. As seen in other studies [35], the CHPs have trust in their supply chain. Cost issues are highlighted as a challenge in which the CHPs would prefer lower prices.

A logistical challenge identified was the dependency on political decisions in the industry where, for example, changes in tax levels and regulations could have potentially large impacts on the industry. The biofuel industry must be viewed as being in competition with other heating options where, for example, taxes imposed on fossil fuel strengthen the relative competitiveness of biofuel. Political dependence is particularly apparent in the municipally owned CHPs. These are not only influenced by general national policies and decisions, but direct political decisions can have significant effects on operations, for example to what extent sustainability issues should guide purchasing, transport, etc. The influence of outside political decisions also runs the risk of reducing the willingness for investment and risk-taking as it introduces an element of uncertainty.

6. Discussion

The logistical implications of the findings indicate that there are limited possibilities for the use of more alternative transports in the supply chain among smaller CHPs. The current supply-chain structure, with orders being placed rather soon before delivery and an unpredictable future demand, fits well with the flexibility and low volume per transport unit offered by road transport. Despite some high-profile implementations of intermodal transport solutions, road is still the most used and clearly most preferred mode of transport, in particular among smaller CHPs, as also shown in previous research [35]. This corresponds to the situation in freight transport in general and in previous research [33], where smaller companies prefer the simpler and more flexible road transport, while transport modes such as rail and sea are mainly used by larger companies with larger flows. Although increased competition for fuel [9] pressures CHPs to source from longer distances, this indicates that smaller CHPs will continue with their current road-based transport solutions.

The use of alternative transport solution also requires a higher logistical competence at the CHP [36], which most smaller CHPs currently lack. A key actor in developing alternative transport solutions is the supplier, as they are often responsible for arranging transport. However, the CHPs maintain a heavy influence over the transport chain, and any radically new transport solution would require the approval of the CHP. This is particularly true among larger CHPs as it is well known in the transport industry that customers with large volumes are more actively engaged in the transport solution and hold more knowledge [60]. Thus, the supplier influence is larger among smaller CHPs, where more advanced transport solutions usually are not an option. This makes the large CHPs of key importance in developing new solutions such as intermodal transport. This is also the case in Sweden where large intermodal biofuel setups have been initiated by the CHPs [6].

The main challenge in increasing the use of alternative transport is reaching the larger volumes required, as previously also shown by Refs. [33,36]. The local focus creates a dispersed network of plants with limited possibilities for supply-chain cooperation, further influenced by the fact that each CHP has specific fuel requirements. Open and cooperative business models integrating the demands of several CHPs have been found to be a potentially interesting way of increasing the use of intermodal transport [36] but are hard to achieve in practice. A further challenge is being able to receive the larger volumes per transport in the alternative modes, as storage capacity is limited by urban sprawl. This imposes a need for external storage sites, which only 35% of the CHPs have. However, the use of external storage might be used to alleviate the limited access to rail and sea infrastructure as the storage can be located by, for example, a rail line. For example, the Igelsta plant (presented in the Introduction) built a storage site and terminal by a rail line a few kilometres from the CHP. Another option to increase the volumes is to place fewer but larger orders; however, the varying demand makes long-term planning difficult. A division can be made here between rail and sea. Rail transport requires a more long-term commitment and thus large, stable volumes. Train setups are negotiated months in advance on a minimum seasonal basis with very limited possibilities for deviations [25], making the costs essentially fixed for the season. A train setup should therefore typically constitute the base flow to the CHP and the demand even during a warm winter should be enough to always fill the train, but this is only the case among the largest CHPs [25]. Further, putting a large volume of fuel on a single transport imposes a supply risk as, for example, a derailment could cause large supply problems. Sea, on the other hand, can be contracted for a single voyage. One of the interviewed CHPs had for example invested in a storage area in a port 80 km from the CHP that was used occasionally when a good opportunity for a larger import purchase of biofuel arose.

There is a strong political will to support the biofuel industry and the use of less environmentally damaging modes of transport. This study shows that there is a need for clear and long-term political strategies to encourage CHPs and logistics companies to make the necessary investments. Similarly, political incentives such as subsidies and reduced taxation might be used to provide further incentives for investments. However, as political decisions can change, this imposes an uncertainty on the industry and has a negative impact on the willingness for long-term investment. It is therefore important for political initiatives to show a consistent and long-term commitment.

7. Conclusions

The characteristics of the industry include a local focus, heavy dependence on road transport and many local actors. Indeed, 61% of fuel is sourced locally (<100 km) from an average of 14 suppliers per CHP, and road is the only transport mode used by 78% of the CHPs. In fact, in almost all cases, all transport less than 250 km is done by road. Transport chains involving rail and sea constitute only 17% of the fuel, mostly relating to the larger CHPs, whose greater demand for fuel forces them to source it from longer distances. Those circumstances open up for rail and sea transport solutions, which require larger volumes, even if they also require the CHPs to take a more active role in arranging the transport of their fuel. Whereas nearly 100% of small and medium CHPs have their transport completely arranged by suppliers, all large CHPs partly do arrange their own transport. When local road transport cannot supply sufficient fuel, CHPs use alternative modes of transport to keep down the cost of long-haul transport. In procuring fuel, the supply chains have a short-term focus—63% of their fuel is ordered less than a week in advance—largely due to unpredictable fluctuations in heating demand. Among other results, cooperation among CHPs in the supply chain is rare because they are geographically dispersed, such that cities seldom have more than one CHP.

Overall, the CHPs are satisfied with the supply system and fuel shortages due to supply failures are not occurring. Although transport operators underperformed relative to service desired for several of the most highly ranked services (e.g. reliability, contamination and cost), they over-performed for the lowest-ranked services (i.e. frequency and transport time), which indicates the potential for improvement. Remarkably, environmental sustainability ranked among the least important factors in transport. Road transport is clearly preferred (i.e. rated 5.5 of 6) with lack of sufficiently large demand for fuel and the absence of infrastructure as the largest challenges for other modes. The logistical challenges identified in Table 13 further highlight hurdles in using alternative modes of transport.

Challenges with extending the use of alternative transport solutions into smaller CHPs relate largely to the need for larger volumes and, an in particular the opportunities of ordering larger volumes at one time. Thus, except for the largest CHPs, road is likely to remain the chief mode of transport for fuel in the future.

In view of those findings, this paper provides new information and a unique perspective on the characteristics of Sweden's biofuel CHP heating industry, supported by quantitative data from an extensive survey. The preferences and logistical challenges identified are used to gauge the possibility of increasing the use of intermodal transport. The paper also further contributes by providing empirical data verifying previous research that was largely based on theoretical modelling. Quantitative data about the biofuel industry's characteristics provided here also allow future researchers to better understand the industry. In any type of research aiming at improving the industry and providing cleaner energy, a thorough understating of the industry is a necessity. In particular, there is a large wealth of research taking a quantitative approaches to modelling the biofuel industry and supply chain (e.g. Ref. [20]) where their efforts can be aided by the detailed overview of the industry provided in this paper. Last, the challenges identified for intermodal transport further contributes the research attempts to design sustainable intermodal transport solutions.

Practical implications of this study include an increased awareness of logistical challenges for CHP managers, as most managers do not have a logistical background. For suppliers, the findings afford details about CHPs' demand preferences, especially regarding flexibility, which may help them to reduce costs by optimising short- and long-term storage volumes. Further, it highlights political- and societal-level challenges posed by the biofuel industry to improve competitiveness and help fulfil the UN Sustainable Development Goals [61], in particular goals 7 (clean and affordable energy) and 13 (climate action). From an international perspective, experience in the well-developed Swedish biofuel industry can help improve the competitiveness of biofuel and cleaner energy in other countries.

Suggestions for future research include expanding the study to other markets, in particular less mature biofuel markets where there is a greater possibility to influence the development of alternative supply chains. This could be combined with a focus on the policy aspect and how this can be supported by appropriate policies. Further, more detailed cost studies are needed based on specific case studies. The current study is limited in the focus on only the Swedish market.

Credit author statement

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Table 13
Summary of the logistical challenges identified.

Challenge	Cause	Effect
Local focus	Geographically dispersed CHPs, each with low volume.	Limits the possible logistical and sourcing solutions and constrains more advanced supply-chain setups. Road transport becomes the main option.
Urban sprawl	Expanding urban areas places old CHPs increasingly in residential and commercial areas.	Imposes operational restrictions on storage areas, chipping, and delivery times, potentially reducing logistical efficiency.
Unknown and varying demand	Demand for heat is dependent on unpredictable outside temperature with significant seasonal variations.	Additional storage is introduced in the supply chain, which needs to be balanced against increased costs and constraints on available storage areas.
Low density of biofuel	Biofuel has low density, in particular before chipping.	Low density limits the full utilisation of transport equipment and increases transport cost. Chipping is performed in the forest with less efficient equipment as the cost of transport is too high to bring fuel unchipped to terminals/CHPs with more efficient equipment.
Dependence on political decisions	Municipally owned CHPs and a national/European political interest in supporting environmentally friendly energy generation.	Competitiveness and logistical setup become partly dependent on outside decisions. Uncertainty over long-term conditions reduces willingness for long-term investments and risk taking.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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